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14. ABSTRACT
The objective was the measurement of the single pass FEL known as the High-Gain, Harmonic Generation FEL. The HGHG approach utilizes a laser-seeded FEL to produce amplified, longitudinally coherent, Fourier-transform-limited output at a harmonic of the seed laser. In the experiment performed at the Accelerator Test Facility at Brookhaven National Laboratory, a seed CO2 laser at a wavelength of 10.6mm produced saturated, amplified FEL output at the second-harmonic wavelength, 5.3mm. The HGHG FEL was demonstrated successfully. The duration of the output pulse was measured using a second-harmonic intensity autocorrelator, and the coherence length was measured using an interferometer. We also measured the energy distribution of the electron beam after it exited the second undulator, observing behavior consistent with that is expected at saturation. The intensity of the harmonic components of the output at 2.65 mm and 1.77 mm were determined relative to that of the 5.3-mm fundamental. Finally, using a corrector magnet upstream of the radiator, steering effects on the trajectories of the electron and light beams were studied.

15. SUBJECT TERMS
Free-Electron Laser; High-Gain; Harmonic Generation; Coherence

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Title of Research Effort

EXPERIMENTAL STUDY OF THE EFFECT OF THE
ELECTRON BEAM QUALITY ON FREE-ELECTRON LASER GAIN

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Programs Long-term Research Objective:
Several configurations of an FEL source are possible. The most widespread configuration involves the use of a high-Q optical cavity and is very effective in wavelength regimes where appropriate mirrors are available. As in the case of lasers, use of an optical resonator can provide a high degree of spatial and temporal coherence. Conversely, the strategy for developing a hard x-ray FEL utilizes a high-gain, single-pass amplifier scheme to circumvent the lack of high quality resonator mirrors at short wavelengths. A straightforward approach to single-pass amplification is referred to as self-amplified spontaneous emission (SASE). In SASE, the spontaneous radiation emitted by quivering electrons near the beginning of a long undulator magnet is subsequently amplified as it co-propagates with the electron beam through the magnetic structure. This process is capable of producing output with high peak power and excellent spatial mode, but a limitation imposed by the random noise buildup is poor temporal coherence, i.e. coherence time much less than pulse duration.

In this research we investigated an alternative single-pass FEL approach, high-gain harmonic-generation (HGHG), capable of providing the intensity and spatial coherence of SASE but with excellent temporal coherence. In the HGHG FEL, a small energy modulation is imposed on the electron beam by interaction with a seed laser in a short undulator (the modulator). The energy modulation is converted to a coherent spatial density modulation as the electron beam traverses a dispersion magnet (a three-dipole chicane). A second undulator (the radiator), tuned to a higher harmonic of the seed frequency (ω), causes the micro-bunched electron beam to emit coherent radiation at the harmonic frequency ($n\omega$), followed by exponential amplification until saturation is achieved. The HGHG output radiation has a single phase determined by the seed laser and its spectral bandwidth is Fourier transform limited.

A major advantage of the HGHG FEL is that the output properties at the harmonic wavelength are a map of the characteristics of the high-quality fundamental seed laser. This results in a high degree of stability and control of the central wavelength, bandwidth, energy and duration of the output pulse. Since the duration of the HGHG radiation reflects the seed pulse characteristics, the output radiation pulse can be made shorter than the electron bunch length by simply utilizing an appropriate duration seed laser pulse synchronized to the electron beam. In fact, high peak power output pulses of a few femtoseconds are possible using chirped pulse amplification (CPA). On the other hand, a short SASE pulse requires an equally short electron bunch, which is presently beyond the state of the art below a few hundred femtoseconds. More problematic is that the temporal profile of the SASE output varies due to the uncontrollable statistical fluctuations of the shot noise that provides the starting signal, and the SASE output is not Fourier transform limited, but a superposition of many wave trains with phases determined by individual electrons.

Program's Objectives:
The objective was the measurement of the single pass FEL known as the High-Gain, Harmonic Generation FEL. The HGHG approach utilizes a laser-seeded FEL to produce amplified, longitudinally coherent, Fourier-

transform-limited output at a harmonic of the seed laser. In the experiment performed at the Accelerator Test Facility at Brookhaven National Laboratory, a seed CO2 laser at a wavelength of 10.6mm produced saturated, amplified FEL output at the second-harmonic wavelength, 5.3mm. The experiment verifies the theoretical foundation for the HGHG FEL and prepares the way for the application of this technique in the vacuum ultraviolet, with the ultimate goal of extending the approach to provide an intense, highly coherent source of hard x-rays.

S&T Completed:

The HGHG FEL was demonstrated successfully. The duration of the output pulse was measured using a second-harmonic intensity autocorrelator, and the coherence length was measured using an interferometer. We also measured the energy distribution of the electron beam after it exited the second undulator, observing behavior consistent with that is expected at saturation. The intensity of the harmonic components of the output at 2.65 mm and 1.77 mm were determined relative to that of the 5.3-mm fundamental. Finally, using a corrector magnet upstream of the radiator, steering effects on the trajectories of the electron and light beams were studied.

Relevance:

The invention of the laser provided a revolutionary source of coherent light that created many new fields of scientific research. Modern laser technology provides versatile performance throughout much of the electromagnetic spectrum. Optical resonators exist in the infrared, visible, and ultraviolet regions of the spectrum, while nonlinear optics is used to extend coverage towards shorter wavelengths (<200 nm). However, the small nonlinear susceptibilities available at short wavelengths result in inefficient photon up-conversion. Thus, an important objective in optical physics is the development of coherent, intense sources at short wavelengths. Work to accomplish this is proceeding in several directions. In particular, there have been advances in high harmonic and x-ray sources generated from intense laser-atom interactions, and in development of plasma lasers (3). However, in the hard x-ray regime (1 Å), the free- electron laser (FEL) emerges as a promising source capable of producing unprecedented intensities. Like synchrotron radiation sources, FELs are based upon accelerator technology. FELs represent an advance over synchrotron radiation, because in an FEL the radiation process benefits from multi-particle coherence, while synchrotron radiation is emitted incoherently, by independently radiating electrons. Consequently, FELs offer the possibility of combining the intensity and coherence of a laser with the broad spectral coverage of a synchrotron.

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A: Title: Accelerator Test facility Operations. Sponsoring agency: Department of Energy. Total funding: $14.5M by FY01. Start date of the award: 10/1/88. End date of the award: NA. The BNL Accelerator Test Facility is a Users facility for research in Advanced Accelerator Concepts and the interaction of high-brightness electron beams and high-power, coherent electromagnetic radiation. The objective is to serve users in national laboratories, universities and industry and allow the development of better particle accelerators and coherent radiation sources.